Identifying a Device for Tracking the Evolution of Thermal Transfer in 3D Printed Parts Using Principles from Axiomatic Design

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Abstract. The evolution in the last decades of the manufacturing processes of parts by 3D printing has revealed the possibilities of changing the material properties of these parts using the values of some of the input factors in the 3D printing process. For the development of experimental research in such a direction, the requirement was formulated to design a device that would allow tracking the evolution of thermal transfer in parts manufactured by 3D printing. In this regard, it was proposed to use a test sample of a lamella made of polymeric material heated at one of the ends. The evolution of the thermal field affecting the sample could thus be followed using an infrared camera. The various components of the test sample support device were identified by applying some principles from axiomatic design. Analysis of the design matrix revealed that a decoupled design was reached. A principle solution was established for the device intended to track the evolution of the thermal field in the sample as a lamella.

Keywords: Heat Transfer, 3D Printed Part, Polymer Lamella, Experimental Device, Axiomatic Design.

1 Introduction

Researching how heat is transmitted through parts made of different materials is of interest both from the point of view of obtaining a faster transfer of the heat released by a heat source and for the better characterization of insulating materials from a thermal point of view. The concept of *heat transfer* refers to the way in which the characteristics of heat are transmitted. In the case of solid bodies, heat transfer occurs by convection. If metals and metal alloys are generally appreciated as good heat-conducting materials, polymeric materials provide lower conditions for rapid heat transmission, being sometimes considered as insulating materials.

Parts made of polymeric materials can be obtained through various processes. The last two decades have highlighted an expansion of manufacturing parts from plastic materials through additive technologies. One such additive manufacturing technology is 3D printing. This technology allows the modification of the manufacturing conditions within wide limits, which facilitates obtaining materials with varied internal structures and characterized, as such, by different heat transmission capacities.

Different experimental research methods have been designed and applied to study the thermal properties of materials in 3D printed parts and therefore the ability of these materials to allow heat transfer.

Thus, de Rubeis et al. generated by 3D printing polylactic acid test samples with different geometries and free spaces inside [1]. Theoretical modeling was used, and, respectively, experimental research in which a heat flow meter and infrared thermography were used to evaluate the way heat is transmitted through these test samples. The thermal insulation capacities of the honeycomb structures were thus confirmed.

High-resolution infrared thermography was used by Muñoz – Codorníu for analyzing anisotropic heat flow in 3D porous architectural structures made of silicon carbide [2]. In this sense, they proposed using a device intended for laboratory applications.

Farzinazar et al. used infrared thermography to study thermal transfer in shape memory polymers embedded in 3D printed samples [3]. They appreciated that the main factors influencing thermal transfer are shape, solid volume fraction, and temperature.

It is noted that there is still research related to the approach of the heat transfer problem using axiomatic design [4-8].

The literature review led to the observation that an experimental investigation of the mode of heat transfer through 3D-printed polymer material parts could be performed using a test sample in the form of a lamella heated at one end. In the present paper, identifying a device solution for supporting the lamella-type test sample was considered using principles from axiomatic design.

2 Considered experiment scheme

The objective pursued was to ensure the conditions for visual highlighting and to evaluate the mode of heat transmission through test samples manufactured by 3D printing from a polymeric material. Different values of the input factors in the 3D printing process were used to manufacture the test samples.

It was preferred to use a lamella-shaped test sample manufactured from a polymeric material by 3D printing (Fig. 1). It was hypothesized that by heating the slide at one end and observing the lamella with an infrared camera, one could track how the test sample heats up over time. At the same time, the temperatures reached during heating in different areas of the lamella could be evaluated. In Figure 1, three arrows indicate the propagation of heat from the support part to the lamella, and the other three arrows indicate heat dissipation by the lamella in the surrounding environment.

If, initially, the lamella will be at the temperature of the surrounding environment, once the heating process of one end of the lamella is initiated, there will be a transfer of heat to the rest of the sample. It is expected that a thermal flow will occur, and it will move from the heated end of the lamella to the rest of the material of the test sample, initially at ambient temperatures. Part of the heat will be transmitted from the lamella to the surrounding environment through the lamella's free surfaces. When the entire amount of heat that enters the lamella from the heated end of it passes through a part of

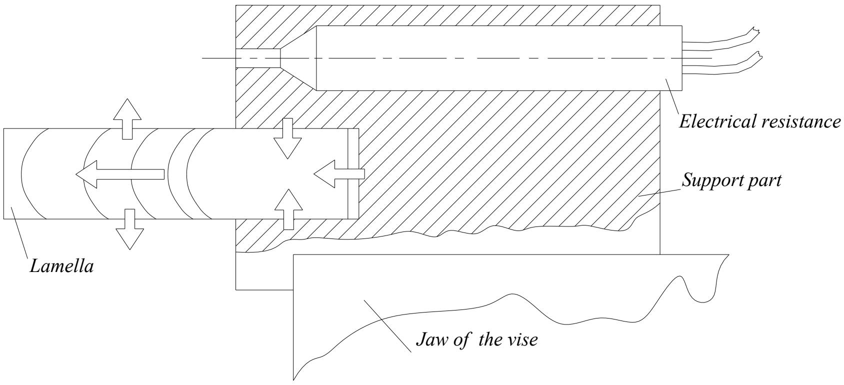

Fig. 1. Hypothesis on how to highlight the transmission of heat with the help of an infrared camera

the test sample and is subsequently discharged to the outside environment, a state of thermal equilibrium will be reached.

The following factors or groups of factors could influence how the heat transfer occurs along the test sample:

- The nature and structure of the lamella material;
- The temperature at which the environment surrounding the free area of the test sample is located;
- Maximum temperature at the heated end of the test sample;
- The speed with which the temperature increases at the heated end of the lamella;
- The dimensions characterizing the cross-section of the test sample;
- The capacity of the test sample material to ensure heat transfer to the external environment;
- The ability of the external environment to absorb the heat transferred by radiation and convection from the test sample.

3 Using some Principles from Axiomatic Design to Design the Device for Heat Transfer Research

Professor Nam Pyo Suh proposed the axiomatic design in the 70s of the previous century. Such a way of designing followed the improvement of manufacturing technologies, but nowadays the axiomatic design is applied to solve problems in very different fields. In principle, axiomatic design involves the use of two axioms: a) The Axiom of independence of functional requirements; b) The axiom of information, according to which the version of the project that requires a minimum of information will be used [6-9]. These principles aim to ensure that the functional requirements of a system are independent and the design is as simple as possible.

Designing a device for the study of heat transfer by using some principles from axiomatic design [9] makes it necessary to define a so-called *customer*. In this situation, it will be considered that the possible client is a Ph.D. student or a young researcher. He must develop research aiming at highlighting the influence of different factors on heat transfer through the materials incorporated in the parts manufactured by 3D printing.

A further sequence will follow the discovery of the customer's need. Following those mentioned above, it will be considered that there is only one customer requirement and that it could be formulated in the following way:

CN: Ensure the existence of a device that allows the study of the influence exerted by different factors on how heat transfer occurs in the material of a test sample manufactured by 3D printing.

Before moving on to the next step, the development of the zero-order functional requirement FR0, it is necessary to mention that the possibilities of using an infrared camera have been analyzed. It is thus known that such equipment (infrared camera) allows highlighting on a screen the temperatures reached in different areas of a body by receiving the infrared radiation emitted by these areas. Using the received radiation, an image is generated on a screen. In this image, areas with different temperatures are represented by different colors or shades of colors..

It is further necessary to develop the so-called *functional requirements FRs*, which should highlight the requests to which the device must respond to satisfy the customer's needs. The zero-order functional requirement may take the form of *FR*0: design a device capable of providing conditions for studying the influence exerted by different factors on the way thermal transfer is carried out in the material of a test sample manufactured by 3D printing. Following the principles of axiomatic design, for the zero-order functional requirement, the statement corresponding to the zero-order design parameter can be formulated: *DP*0: Device that ensures conditions for researching the influence exerted by different factors on how heat transfer occurs in the material of a 3D printed test sample. These design parameters will represent the technical features that can fulfill the FRs to gather them all together to obtain the proposed solution for the equipment.

The next stage of applying axiomatic design principles aims to decompose the zero-order requirement into first-order requirements. Subsequently, each zero-order functional requirement will be associated with a zero-order design parameter. Each *FR* will correspond to a specific *DP* as an applicable technical solution.

A review of the main requirements with the highlighting of the solution found as a design parameter that the tracked device will need to meet could be as follows:

*FR*1: Determine the shape of the test sample intended to allow the study of heat transfer evolution. It can be mentioned here that the results obtained through previous experimental tests that followed the thermal transfer, in more limited conditions, through some cylindrical polymer rods manufactured by 3D printing [10] were taken into account. The obtained results showed that it is more difficult to formulate general observations regarding the thermal transfer for such situations due to the cylindrical bar's relatively large thickness and the cross-section's specific circle shape. The design parameter that arose after formulating the functional requirement of *FR*1 was to use a plate-shaped test sample with a rectangular cross-section and sufficiently thin. Heating at one end of the test sample should allow a clearer image of how the heat is transmitted along the thin, constant-thickness lamella. Based on the second axiom of the axiomatic design [11, 12], the two types of test samples considered (the one in the form of a cylindrical bar with a circular section and, respectively, the one in the form of a lamella with a rectangular cross-section), the test sample variant in the form of a thin lamella, with a rectangular cross-section, was selected. There is a higher probability of success in the case of this variant to the first alternative since the lamella type test sample would allow obtaining an image closer to what the CN customer's requirement contains;

For the next *FRs*, the same approach was applied so that the dependence matrix FRs-DPs could be created at the end.

*FR*2: Provide a body of the device (support part) to which some of the other components will be assembled, such as those for locating and clamping the lamella, heating one end of the test sample, determining and adjusting the value of the heating temperature, etc. This device body could be of the monobloc type, as a body obtained by assembling distinct components could also be considered. For now, by also taking into consideration axiom two, a monobloc-type body was preferred;

*FR*3: Provide conditions for controlled heating of one end of the test sample. Among the various solutions to meet this requirement (flame heating, induction heating, heating using an electric resistance, etc.), the use of an electric resistance was preferred since it ensures simpler conditions for assembly and controlled heating of the part support and, through it, the end of the lamella-shaped test sample;

*FR*4: Provide conditions for supplying electrical current to the electrical resistance. It was assessed that it is the taking of energy from the outlet corresponding to the electrical network of the laboratory where the experimental research is carried out. The electric heating resistance will be supplied with electric current through a controller that allows the adjustment and maintenance of the temperature variation between certain limits to the temperature determined using a temperature sensor;

*FR*5: Provide possibilities for programming and controlling temperature values. The previously mentioned temperature controller and sensor could help meet this requirement;

*FR*6: Provide conditions for assembling the subsystem corresponding to the temperature sensor to the support part.

*FR*7: Provide conditions for placing the device on a locksmith table in the laboratory. The experience accumulated through previous research [10] highlighted the need to use lower temperatures (around 60-100 °C) to avoid reaching a temperature at which the material of the test sample could reach a state of plasticity. The solution identified for this purpose could involve the use of a vise. The previously mentioned reason and the relatively high thermal conductivity of the vise parts' metal material were considered. Since the support part will heat itself, it may be necessary to use an intermediate part made of a material with low thermal conductivity and placed between the support part and the vise. It was thus estimated that the vise components would be relatively low heating, making the use of the intermediate piece unnecessary.

As previously mentioned, the corresponding design parameters in the form of solutions found were also identified for each functional requirement. A synthetic presentation of the correlations between the first-order operating requirements and the first-order design parameters can be seen in Table 1.

For some of the highlighted functional requirements, it is possible to resort to the continuation of the decomposition activity by generating the second-order functional requirements.

Table 1. The matrix containing *FRi* functional requirements and *DPi* design parameters in the case of the equipment for the study of thermal transfer in the polymeric material of a test sample manufactured by 3D printing.

1	Design parameters		DP0: device to allow the study of the influer exerted by different factors on the way therm transfer takes place in the material of a sam manufactured by 3D printing.						
2	Functional requirements		*DP1*: Proba de testare sub forma unei lamele	*DP2*: Monobloc support piece	*DP3*: Electrical resistance	*DP4*: The electrical network	*DP5*: Controller and temperature sensor	*DP6*: Subsystem for assembling the sensor	DP7: Vi...
3 Column no. 1	2	3	5	6	7	8	9	10	1
4	Zero order functional requirement	1st order *FR* functional requirements	Highlighting the *DPi* design parameters corresponding to each *FRi* functional requiremen						
5	*FR0*: design a device capable of providing conditions for studying the influence exerted by different factors on the way thermal transfer is carried out in the material of a sample manufactured by printing	*FR1:* Determine the shape of the specimen intended to allow the evolution of heat transfer	X						
6		*FR2* Provide for a device body (a support part) to which some of the other components will be assembled		X					
7		*FR3*Provide controlled heating of one end of the test sample		X	X				
8		*FR4*: Ensure the electrical current supply to the electrical resistance				X			
9		*FR5*: Provide programming and control of temperature values		X		X	X		
10		*FR6*: Provide conditions for assembling the subsystem corresponding to the temperature sensor to the support piece						X	
11		*FR7*: Secure the placement of the device on a locksmith table in the laboratory		X					X

For example, in the case of functional requirement *FR*2, the following could be considered:

*FR*2.1: Determine the basic shape of the support part;

*FR*2.2. Determine the material of the support part;

*FR*2.3. Ensure the locating and clamping of the test sample in the support part;

*FR*2.4. Ensure the shape and position of the clearance for the temperature sensor.

These functional requirements could be assigned the following *DPi* design parameters:

*DP*2.1. Support part in the form of a plate, with the removal of material from areas where it is not needed;

DP2.2. Aluminum. It could also be considered to use copper to make the support part, but this material is more expensive;

DP2.3. A clearance to facilitate the self-clamping of the test sample, preferably a clearance whose flat walls form an angle of about 20 °. It is noted, at this moment, that exploiting the zig-zagging facilities [12], it is necessary to modify the design parameter *DP*1: the test sample must have the shape of a lamella, but the end that will be used to locate and clamp the test sample will have to have flat walls arranged at an angle of 20 ° (Fig. 2, a). Other ways of locating and clamping the test sample could be considered,

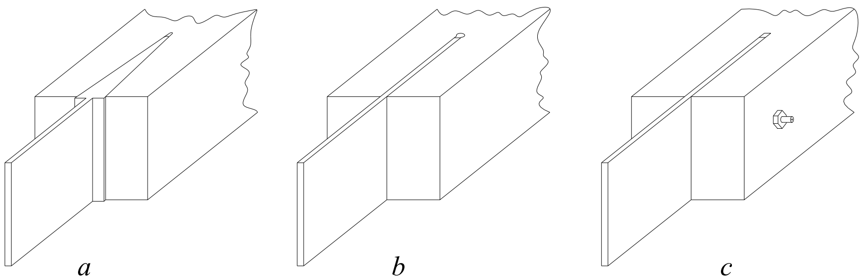

Fig. 2. Variants taken into account when establishing the design parameter *DP*2.3.

for example, by using a parallel-walled clearance with some elasticity to immobilize the test sample (Fig. 2, b), or the clamping could be by using screws and nuts (Fig. 2, c). It was appreciated that the angular release would allow a more efficient transfer of heat through the inclined walls, and at the same time, it is simpler than the variant that involved the use of screws and nuts. Therefore, the requirement corresponding to the second axiom seems to consider the variant with angular release as having a higher probability of success.

DP2.4: Threaded hole located perpendicular to the axis of the cylindrical surface corresponding to the electrical resistance subsystem (the latter being a commercially available component).

The matrix equation corresponding to the functional requirement *FR*2 can now be written:

$$\begin{Bmatrix} FR2.1 \\ FR2.2 \\ FR2.3 \\ FR2.4 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ X & 0 & X & 0 \\ X & 0 & 0 & X \end{bmatrix} \cdot \begin{Bmatrix} DP2.1 \\ DP2.2 \\ DP2.3 \\ DP2.4 \end{Bmatrix}. \quad (1)$$

The analysis of the information in Table 1 and in Equation (1) highlights that in both situations, we are dealing with *a decoupled design* since fulfilling some functional requirements requires the involvement of two design parameters. The obtained result can be represented in the form of an upper triangular matrix. It can be seen that revealing the correlations between the functional requirements *FRs* and the design parameters *DPs* led to the placement of "*X*" symbols below the descending diagonals of the matrix representation.

Certain constraints were also considered in the design of the schematic diagram of the device. Such constraints referred to the need to identify a solution that is not too complex and has dimensions that allow the support piece to be fixed in an existing laboratory vise. Another constraint was that the components of the device could be purchased from the trade or require only processing that can be done on the machine tools of the laboratory.

4 Proposed Solution

The solution, whose schematic representation can be seen in Figure 3, was proposed by considering the results of applying some axiomatic design principles. It is noted that the area of the lamella that protrudes outside the support part can be examined and filmed using an infrared camera. The heating of the support part is made using electric resistance. Achieving and maintaining a low variation of a pre-set temperature by the support part is possible using a temperature sensor and controller.

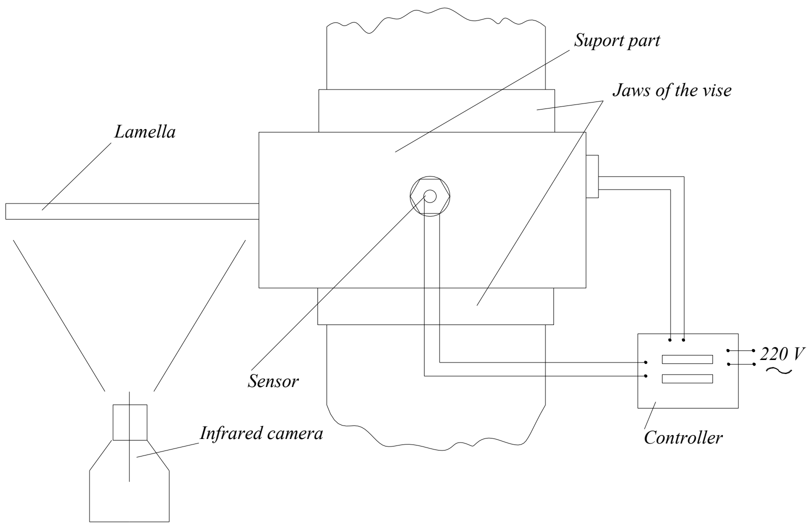

Fig. 3. Schematic representation of the proposed solution.

5 Conclusions

The need to design a device that allows the investigation of the influence exerted by some factors on the evolution of thermal transfer inside some test samples of polymeric material manufactured by 3D printing was taken into account. It has been appreciated that a lamellar specimen provides general information on how heat is transmitted through the test sample when one end of the test sample is heated. Some axiomatic design principles were used to identify a solution corresponding to the device for supporting and heating the test sample. In this sense, the main functional requirements of the first order were formulated, to which the corresponding design parameters were attached. When a functional requirement could be met in more than one way, the second axiom of the axiomatic design was used to select the alternative that could provide the highest probability of successful use of the device. The development of the design matrix led to the observation that the proposed solution corresponds to a decoupled design. By applying the axiomatic design, a device was proposed that would allow the highlighting of the heat propagation way inside a parallelepiped plastic test sample manufactured by 3D printing. The intention is to realize and experimentally test the proposed device. Later, research will be carried out regarding the behavior of different plastic materials and distinct internal structures of the test samples made by 3D printing from the point of view of heat propagation through thermal conduction.

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